

## XMM-NEWTON EPIC OBSERVATIONS OF HER X-1

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## ABSTRACT

We present spin-resolved X-ray data of the neutron star binary Her X-1. We find evidence that the Iron line at 6.4 keV originates from the same location as the blackbody X-ray component. The line width and energy varies over both the spin period and the 35 day precession period. We also find that the correlation between the soft and hard X-ray light curves varies over the 35 day period.

Key words: accretion, accretion disks – X-rays: binaries – individual Her X-1 – stars:neutron

## 1. INTRODUCTION

Her X-1 is a stellar binary system consisting of a neutron star and a A/F secondary star. It has been extensively studied at many wavelengths. Its main temporal observational characteristics are: the spin period of the neutron star is  $\sim 1.24$  sec, the binary orbital period is 1.7 day and there is a 35 day period seen in X-rays which has been interpreted as due to a warped accretion disc precessing around the neutron star. We have obtained three observations of Her X-1 made using XMM-Newton at 3 different epochs. In this paper we present an analysis of spin resolved data obtained using the EPIC detectors.

## 2. OBSERVATIONS

The details of our observations are summarized in Table 1. To determine how these epochs relate to the 35 d precession period ( $\Phi_{35}$ ), we extracted the RXTE ASM (2-10) keV quick-look light curve (Figure 1). This shows that the first observation took place close to maximum X-ray brightness ('main-on'), while the third was close to the secondary maximum ('short-on'). The second observation took place after the end of the main-on state ('faint-state').

The EPIC detectors were configured in timing mode (apart from MOS2 which was in full frame mode and heavily piled-up). In the second observation, data at the start and end of the observation were excluded because of a higher particle background. Because of difficulties in extracting background light curves and spectra in timing mode, our data are not background subtracted. Since Her

Observation Date	Effective Exposure (ksec)	EPIC PN Mean ct (ct/s)	Orbital Phase	35 d Phase ( $\Phi_{35}$ )
2001 Jan 26	10	398.4	0.20–0.26	0.17
2001 Mar 4	11	21.4	0.47–0.56	0.26
2001 Mar 17	11	54.3	0.52–0.60	0.60

Table 1. Summary of the XMM-Newton observations of Her X-1. For the orbital phasing we use the ephemeris of Still et al (2001); for the 35 day phasing we define phase 0.0 as point of the main high state turn-on.

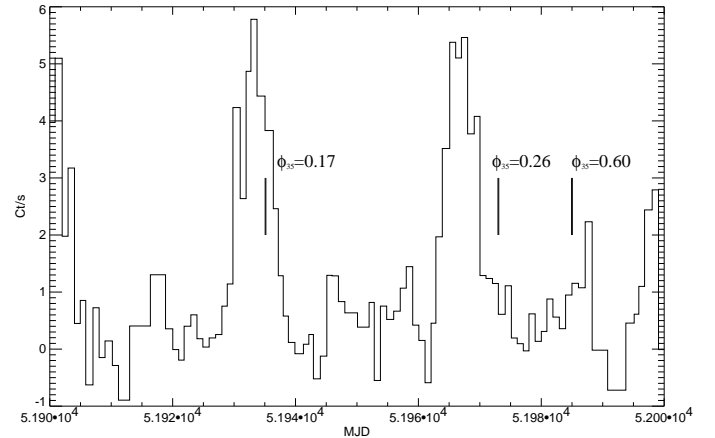


Figure 1. The RXTE/ASM (2-10) keV light curve of Her X-1: the thick lines indicate the XMM-Newton observations.

X-1 is much brighter than the background in each epoch, we do not expect that this will have a significant effect on our results. We have analysed both EPIC MOS1 and EPIC pn data. The results from each detector are consistent and here we show the results based on the pn data. Data were processed using version 5.2 of the XMM-Newton Science Analysis System.

## 3. SPIN RESOLVED LIGHT CURVES

A barycentric correction and a correction for the motion of the neutron star around the binary center of mass (using the ephemeris of Still et al 2001) was applied to each photon. We then used a discrete Fourier transform to obtain the spin period in each of the 3 epochs. Because of the problems with the clock on-board XMM-Newton these periods differ to some extent from that expected from the

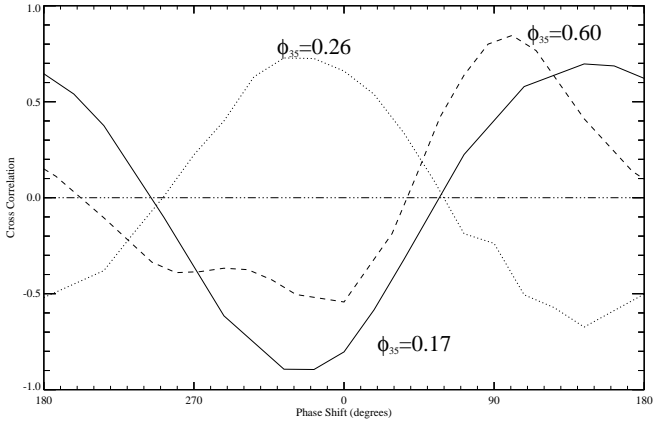


Figure 3. The cross correlations for the soft and hard energy resolved light curves at the 3 epochs.

recent spin history of this object (eg Oosterbroek et al 2001). Since this study is concerned with the relative phasing of the different energies rather than the precise spin period, we are confident that since we have used the most prominent peak in the power spectra our results are robust.

We show in Figure 2 the energy-resolved spin-folded light curves in our 3 observations. In the main-on state ( $\Phi_{35}=0.17$ ) the softest (0.3–0.7 keV) and the harder ( $>2$  keV) light curves are anti-phased with some evidence that the minimum of the continuum subtracted 6.15–6.7 keV light curve matches the peak of the harder curves. In the faint-state ( $\Phi_{35}=0.26$ ) the modulation is much reduced, being greatest above 7 keV. The soft and hard curves are approximately in phase. By the short-on state ( $\Phi_{35}=0.60$ ) we find that the peak of the hard light curves corresponds to the minimum of the softest.

To investigate this more fully, we show the cross correlation of the soft and hard light curves in Figure 3. In the main-on state we find that the most prominent cross correlation peak shows that the soft and the hard light curves are strongly anti-correlated, with only a small phase lag ( $\sim -30^\circ$  or  $330^\circ$ ). We also find another (positive) peak at ( $\sim 130 - 170^\circ$ ) which corresponds approximately to the separation between the peaks in the soft and hard light curves. The faint state shows a positive correlation at small phase lag ( $\sim 330^\circ - 340^\circ$ ) and a negative correlation at  $\sim 130 - 160^\circ$ . During the short-on state, we find the highest correlation near  $\sim 100^\circ$ . It is clear that the relative phase shift between the soft and hard X-ray light curves varies as a function of the 35 d precession period.

#### 4. PULSE PHASE SPECTROSCOPY

To search for a variation in the profile of the Fe line at 6.4 keV over the spin cycle, we extracted spin resolved spectra. We ignored energies less than 5 keV and more than 8 keV and used a Gaussian plus power law model to model the spectra. We also determined the variation in the power law normalisation by fitting an absorbed power

law over the range (2.0–6.1) keV and (6.7–10) keV, after fixing the slope to be that of the best fit of the appropriate integrated spectrum. Results are shown in Figure 4, together with the soft and hard light curves.

At  $\Phi_{35}=0.26$  there is no significant variation in the line parameters. At phase  $\Phi_{35}=0.60$  there is marginal evidence that the minimum of the equivalent width corresponds to the maximum of the intensity in the (2–4) keV band. At  $\Phi_{35}=0.17$  there is some evidence that the line width reaches a minimum at the maximum of the intensity of the (2–4) keV light curve, but the most interesting result is that the equivalent width curve clearly follow the soft X-ray light curve. This supports the idea that the 6.4 keV fluorescence Fe line and the black body component originate from a common region.

## 5. DISCUSSION

### 5.1. ENERGY RESOLVED LIGHT CURVES

Many features of the light curves are naturally explained within the scenario proposed by Scott et al 2000. This model is based on the obscuration of a multi-component X-ray beam by a counter-precessing, tilted, twisted disk. For simplicity, the X-ray beam is assumed to be decoupled from the disk and is axisymmetric. One of the main features of this model is that it ascribes the variations observed in the pulse profile over the 35 day cycle to occultation from the *inner* part of the disk, whereas most of the previous investigations have assumed an occultation from the *outer* boundary.

The overall situation is summarized in the bottom panel of Figure 8 in Scott et al 2000, while their Figures 10 & 11 illustrate the evolution of the pulse profiles predicted during the main-on and short-on respectively. There is a similarity between the multi-peaked hard light curve at  $\Phi_{35} = 0.17$  and the model during the progressive occultation of leading and trailing peaks of the hard beam. At  $\Phi_{35} \sim 0.27$ , when the main components are occulted, we only observe the survival of a broad, underlying modulation that is attributed to the magneto-spheric emission. Since this component is emitted from a larger region at some distance from the neutron star, it is naturally expected to have a lower modulation as well as a broad maximum.

The pulse profile close to the short-on is also similar to that presented by Scott et al 2000 at  $\Phi_{35} \sim 0.58$  (see their Figure 11). In the EPIC data, we can in fact recognize a main peak “A” as well as a small peak “B” (Figure 2). However, because the notch “B” is the hardest feature, spectral considerations suggest that this maximum is associated with the small hard peak and the feature “A” with the soft peak discussed by Scott et al 2000. If this is the case, “B” is actually due to direct emission from the pencil beam, while “A” is the radiation redirected into the fan beam from the antipodal accretion column.

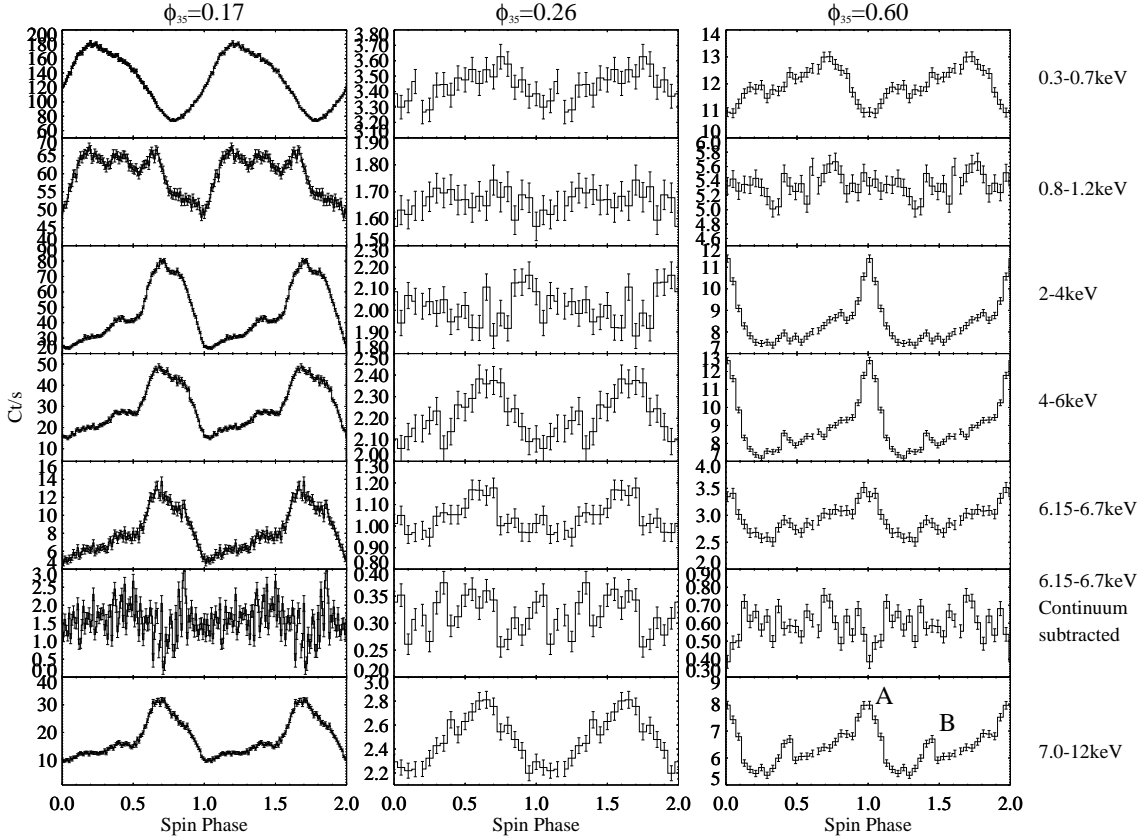


Figure 2. The spin profiles for various energy bands for the three epochs (left to right: the main-on, faint and short-on states). Because of the uncertainty in the absolute timing, the spin phases are not on the same absolute scale.

## 5.2. THE SHIFT BETWEEN THE SOFT AND HARD CURVES

Given the complexity of the source, pulse-phase spectroscopy is of paramount importance to separate the different spectral components observed in Her X-1. Using *Einstein* and *BeppoSax* data it has been shown that, during the main-on state, the maximum of the thermal component and the power law components are shifted by  $\sim 250^\circ$ . The situation is less consistent as far as the 6.4 keV Fe K line is concerned: Choi et al 1994 have shown that its intensity is modulated in phase with the soft emission, suggesting a common origin while Oosterbroek et al 2000 have found it correlated with the hard (power law) emission.

The shift in phase between the hard and soft emission can be explained if the latter results from re-processing of hard X-rays in the inner part of the accretion disk. If a non-tilted disk intercepts (and re-processes) a substantial fraction of the hard beam from the neutron star, the expected phase difference between direct and reflected component is  $180^\circ$ . Therefore, the value determined using *Einstein* and *BeppoSax* data has been associated with the disk having a tilt angle. If the tilt of the disk changes with the phase along the 35 day cycle (as predicted by the

precessing disk models, see Gerend & Boynton 1976) the shift in phase should therefore vary with  $\Phi_{35}$ . However, both *Einstein* and *Sax* data were obtained at the same  $\Phi_{35}$ .

The phase shift derived from *XMM-Newton* data main-on state data are considerably different from previous observations made in the main-on state and continues to change during the other two observations. This suggests that we are observing, a *substantial and continuous variation in the tilt of the disk*, which is what we would expect from a system which had a precessing accretion disc. It should be noted that the interpretation of the phase shift observed at the short-on may be affected by a systematic error, depending on whether during the observation the soft peak “A” is higher than the small hard peak “B” or vice-versa.

## 5.3. THE FE 6.4 KEV LINE VARIATION

At  $\Phi_{35} = 0.26$ , there is little evidence for a significant variation in the Fe line parameters, while at  $\Phi_{35} = 0.60$ , there is some evidence that the variation of the equivalent width of the Fe line is in anti-phase with the (2–4) keV intensity

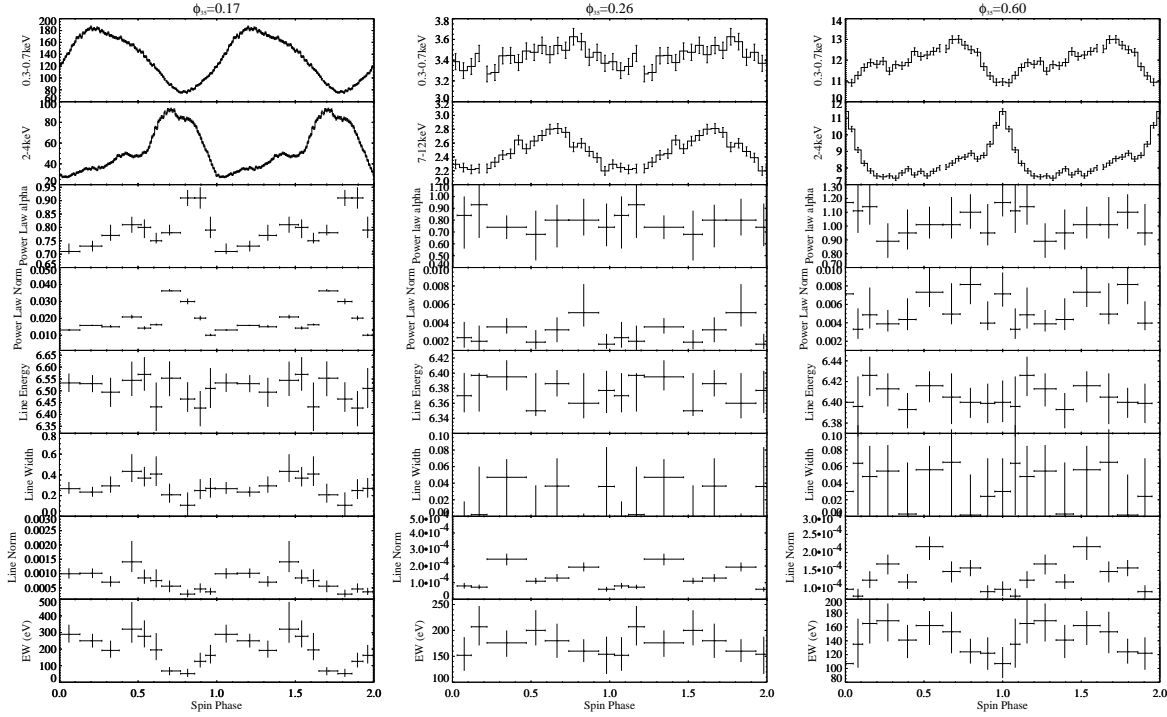


Figure 4. The variation of the Fe line parameters as a function of the spin phase, for the three different epochs. We also show the normalization of the power law component and the intensity curves in the soft (0.3-0.7 keV) and hard energy band. The latter is taken to be (2-4) keV for  $\Phi_{35}=0.17$ ,  $\Phi_{35}=0.60$  and (7-12) keV for  $\Phi_{35}=0.26$ . The line width is the FWHM in keV.

curve and follows the general shape of the (0.3–0.7) keV intensity curve. At  $\Phi_{35} = 0.17$ , we find that the soft flux below 0.7 keV, the line normalization, the line width and the equivalent width all exhibit a common minimum at  $0.7 < \phi_{spin} < 0.9$ , which, in turn, is shifted with respect to that of the hard emission. This supports the idea that the 6.4 keV Fe line originates from fluorescence from the relatively cold matter of the illuminated spot where the soft emission is reprocessed.

We have also found evidence for a variation in the Fe line broadening over the 35 day period. In addition, the energy of the Fe line suggests that the Fe line emission originates from low ionisation species (Fe XIV or less) in the low and short-on state observations, whereas in the main-on the observed Fe K centroid energies ( $6.52 \pm 0.03$  keV for MOS and  $6.50 \pm 0.02$  keV for PN) correspond to Fe XX-Fe XXI.

Taking this into account, the true centroids deviate by  $\sim 7\sigma$  from the 6.40 keV neutral value. This suggests two possible explanations for both the line broadening and the centroid displacement: 1) an array of Fe K fluorescence lines exists for a variety of charge states of Fe (anything from Fe I-Fe XIII to Fe XXIII); 2) Comptonization from a hot corona with a significant optical depth for a narrower range of charge states centered around Fe XX.

The Fe line broadening may also be explained in terms of Keplerian motion, if the inner disk (or some inner region) comes into view during the main-on state. If this is the case, at  $\Phi_{35} = 0.17$  the Keplerian velocity will be  $\sim 13000$  km/sec. This, in turn, corresponds to a radial distance of  $\sim 4 \times 10^8$  cm (for a neutron star of  $1.4\odot$ ), which is close to the magneto-spheric radius for a magnetic field of  $\sim 10^{12}$  G.

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